G+ Examining the impact of floating wind turbines on the human operator: A scoping review

G+ Global Offshore Wind
Health & Safety
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EXAMINING THE IMPACT OF FLOATING WIND TURBINES ON THE HUMAN OPERATOR: A SCOPING REVIEW

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FOREWORD

In November 2022 the *G+ conducted a Safe by Design workshop on Floating Offshore Wind: Transfers, access and egress*, and materials handling (report available on the G+ website). The first recommendation of that report was for industry to conduct research into motion and its short- and long-term impacts on the human body. The G+ requested the support of Dr Milligan and Prof. Tipton to conduct a scoping exercise to review the potential implications of floating wind technology on the human operators, provide potential mitigation strategies and recommendations for research direction. This report is the result of that exercise. The G+ workstream on Floating Wind is now considering the recommendations herein and how best to take them forward.

ACKNOWLEDGEMENTS

The G+ gratefully acknowledges Dr Gemma Milligan and Prof. Mike Tipton of the University of Portsmouth for conducting this scoping review and for their time engaging with G+ members throughout this process.

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1 SCOPE

In recent years, the development of offshore wind power has been favoured due to the strength of wind resources over the ocean compared to land. However, a significant limitation has been the reliance on fixed structures, preventing installations in deep or complex seabed locations, with the introduction of floating structures, this barrier has been overcome. The emergence of floating offshore wind turbines (FOWT) is raising concerns about the impact on individuals responsible for maintaining these installations. The motion experienced by FOWT is likely to be associated with low-frequency vibrations (<0,5 Hz), which have been linked to physical and cognitive performance degradation. This degradation can manifest in postural instability, motion sickness, and motion-induced fatigue. The objective of this scoping exercise is to provide an overview of the implications of floating wind technology on human operators during all phases of the life cycle of the turbine (i.e. commission, operation and decommission) and provide recommendations for potential mitigation strategies and future research directions.

2 INTRODUCTION

The emergence of floating wind installations requires designers (both of the turbines and floaters), regulators and operators to consider the additional demands that may be placed on the individuals working on these new installations. Due to the potentially novel and complex nature of the operating conditions created by having a floating platform, a number of questions regarding the impact on individuals need to be considered in relation to personal safety, human comfort and the ability to work.

One key consideration when working on FOWT is motion. Installations will be further out to sea and therefore likely to experience greater sea states, which will impact safe access/egress (Figure 1), ultimately increasing downtime (Scheu et al., 2018), and have the potential to affect aspects of commissioning and decommissioning of turbines. Additionally, the magnitude of low frequency vibrations motion (i.e. less than 0,5 Hz) that could impact work productivity is yet to be fully quantified. Sections 2.1 and 2.2 provide an overview of the relevant literature.

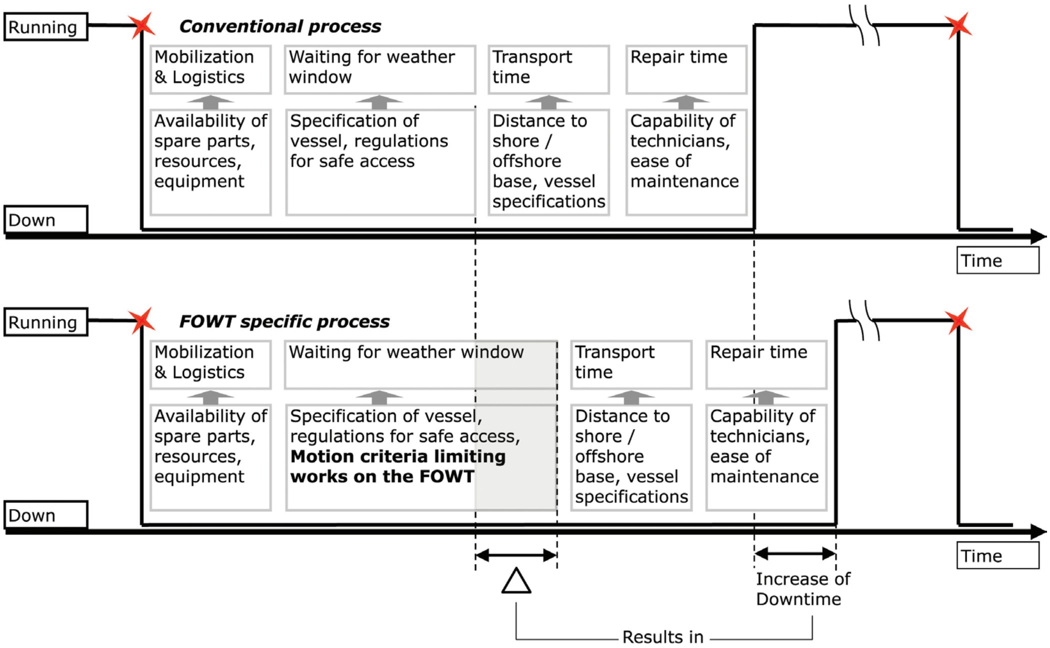

Figure 1: Potential impact of motion criteria on downtime (Scheu et al., 2018)

2.1 FLOATING OFFSHORE WIND TURBINES

A number of review articles have been conducted on the design challenges of FOWT (Wang et al., 2010; Henderson et al., 2010; Musklus & Schafhirt, 2014; Lui et al., 2016; Leimester et al., 2018; Wu et al., 2019; Chen et al., 2020) and future trends (Rinaldi et al., 2021), yet none of these articles considered the impact working on FOWT would have on individuals during troubleshooting and maintenance activities (McMorland et al., 2022).

The motion experienced by FOWT will introduce added complexities for individuals, for example, accessing and exiting the installation and carrying out essential job tasks, particularly if weather windows are shortened, and transfers prolonged. This shift could heighten the challenge of conducting on-site inspections repairs, and maintenance primarily because of the inherent dynamics associated with floating wind turbines. Therefore, consideration when modelling the performance of FOWT should include the safety of individuals engaged in activities on the floating structure (McMorland et al., 2022). Kaptan et al. (2022) considered workability of individuals, when modelling the motion and performance of a spar buoy and semi-submersible concept (Figure 2). They applied the concept of a workability index as a measure for the workable time relative to all available time below a given significant wave height, based on relevant motion and acceleration limiting criteria (i.e. ranges between zero and one, where a workability index of 1 corresponds to 100 % workability, Kaptan et al. (2022).

These data were calculated using the JONSWAP and Torsethaugen wave spectrum analysis (Hasselman et al., 1973; Torsethaugen et al., 2004). Data were based on the general operability limiting criteria for ships first established in the NORDFORSK study[1] (Table 1).

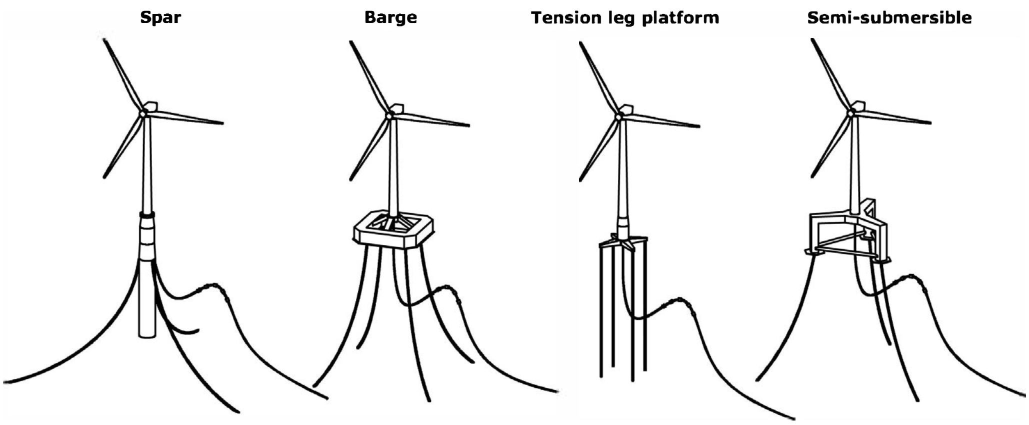

Figure 2: Floating offshore wind turbines substructure design classes (Scheu et al., 2018)

Table 1: Set of criteria with regards to vertical/lateral accelerations and rotational displacement (NORDSFORK, 1987 cited by Kaptan et al., 2022)

Description	Vertical acceleration (RMS)	Lateral acceleration (RMS)	Rotational displacement (RMS)
Light manual work[a]	0,20 g	0,10 g	6,0’
Heavy manual work	0,15 g	0,07 g	4,0’

1 The Nordforsk study (1987), book reference NORDFORSK, G., 1987. Assessment of ship performance in a seaway. Results of a Nordic co-operative project on seakeeping performance of ships, has been referenced in multiple sources, however the original text could not be sourced.

Table 1: Set of criteria with regards to vertical/lateral accelerations and rotational displacement (NORDSFORSK, 1997 cited by Kaptan et al., 2022) (continued)

Description	Vertical acceleration (RMS)	Lateral acceleration (RMS)	Rotational displacement (RMS)
Intellectual work[b]	0,10 g	0,05 g	3,0′
Transit passenger[c]	0,05 g	0,04 g	2,5′
Cruise liner	0,02 g	0,03 g	2,0′

[a] Tolerable less than 1 hour (Dolinskaya et al., 2009)

[b] 0,5 hours exposure for people unused to ship motions (Payne et al., 1976)

[c] 2 hours exposure for people unused to ship motions (Payne et al., 1976)

Wave height became the limiting factor for workability across all concepts and locations. Workability on the platforms was found to be one for wave heights up to 5 m when working at the level of the transition piece. This dropped to 3,5 m when moving up to the nacelle. Whilst this sets an upper working limit for FOWT, there are a number of considerations:

i. What operational limits are based on. Current operational limits are strongly dictated by the ability of the vessels or helicopters used to transfer individuals. Data have shown that, depending on the vessel, these wave heights could vary from 1,5 m to 5 m (Hu et al., 2019). Based on current findings, it would suggest that individuals should not be working in the nacelle in wave height above 3,5 m.

ii. Scalability of these data. Models were produced for nacelle heights at 0 m, 1,7 m and 89,6 m. As turbines increase in size are these data still valid?

iii. Location specifics: the locations modelled were Norway and South Korea. Are these valid for all areas, e.g. North Sea, UK?

iv. Whilst workability was reported, it was not reported in the context of exposure times. Data presented in Table 1 refer to the type of work and duration of exposure. The impact of these are not discussed, i.e. exposures were given up to a maximum of 2 hours. Therefore, are these data valid for working days of 8 to 10 hours?

v. Lateral and vertical accelerations reported may not directly affect workability, but could potentially fall outside guidance set for motion sickness (Section 2.2.2, Table 3). Therefore, when examining the motion of FOWT, motion illness criteria should be considered and examined.

2.1.1 Maintenance activities

Scheu et al. (2018) used computer modelling to examine personnel safety, human comfort and the ability to work on a FOWT. The focus of this study was on the influence that structural motion could have on individuals located on the asset in a harsh environment during maintenance activities.

The data revealed that low frequency motion, which is the predominant motion characteristic of floating wind assets, is not covered in the required detail within many of the models being produced. The vast majority of available literature addresses motions in frequency ranges above 1 Hz; the assets considered by Scheu et al. (2018) were operating in a range up to 0,5 Hz. The lack of guidance and research specific to FOWT has led to the application of practical recommendations that have been derived from shipping, fish farming, military and other naval industries.

Another significant impact of FOWT is the reduction of safe maintenance windows as dictated by potentially more extreme weather fronts, ultimately impacting the time in which essential work tasks may be carried out (Scheu et al., 2018). Human comfort may also increase potential operating windows and requires further investigation. It has been postulated an additional 5 % of the time in which an asset is accessible (depending on design, and wave heights between 1,5 m and 3,5 m), accelerations would be in a range that would be unacceptable for individuals to carry out their work (Scheu et al., 2018). The potential production losses due to this situation are significant, considering large offshore wind farms. It has been recommended that future work should more accurately quantify the potential losses associated to the factor of workability across different wind turbine sizes and park layouts (Scheu et al., 2018), with considerations given to solutions such as increasing team sizes assigned to carry maintenance.

Of note (Scheu et al., 2018):

i. Workability was not necessarily reported to become worse at higher sea states. The response of the FOWT, leading to high accelerations, could be more significant in low wave height and low frequency wave states. This is in contrast to the later work of Kaptan et al. (2022), therefore further investigation is needed.

ii. In less than 5 % of all cases studied, during all sea states, translational acceleration threshold values were being exceeded (i.e. accelerations experienced by personnel would exceed safety thresholds), with rotational accelerations causing non-workable conditions.

iii. These factors lead to the recommendation that in the design stage the influence of human comfort criteria must be taken into consideration. The factors influencing workability are aside from the environmental conditions, structural design and the eigenfrequencies (i.e. the natural frequencies at which the FOWT will oscillate when subjected to external forces or disturbances) of FOWT.

2.1.2 Motion exposure

The motion of the FOWT will be one of the biggest challenges for operations and maintenance (O&M) activities, impacting transfer safety (either from vessels or helicopters) and personal comfort. The work in this area is currently limited, with no thought being given to physical work capacity. Therefore, accurate models are needed to further understand workability and to allow for human experimentation to take place.

The proneness to motion illness (sickness) and other motion-related responses by the human body are highly individualised (Irmak et al., 2023). Whilst some individuals could be able to work under highly severe conditions, others may get motion illness during low sea states (Scheu et al., 2018).

The authors of this report could not find any specific studies relating to motion illness, postural stability, cognitive performance, motion-induced fatigue (central and peripheral) in relation to work performance specifically on FOWT. Laboratory studies and/or site investigation are needed to explore the implications of FOWT on medical and physical employment standards and the effects of motion exposure with respect to the duration and quality of essential job tasks carried out under different conditions.

2.2 INSIGHTS FROM OTHER INDUSTRIES

It is widely accepted that physical and cognitive degradation occurs due to low frequency vibration (i.e. less than 0,5 Hz) that can be grouped into three categories: postural stability; motion illness and motion-induced fatigue (Figure 3, based on Powell et al., 1999). A fourth category, whole body vibration, is experienced at higher frequencies, and likely experienced when working on a turbine, e.g. when using hand-held tools (Kaptan et al., 2022).

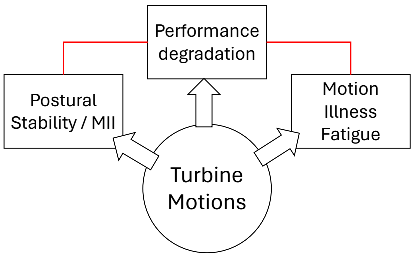

Figure 3: Potential direct and indirect effects of turbine motion on human performance, adapted from Powell et al., (1999) using ship motion data *MII = Motion-induced interruptions due to a loss of balance

2.2.1 Postural stability

Postural stability has been defined as the capacity of an individual to manage their bodily orientation in the surrounding environment, facilitating movement, balance, and engagement in physical tasks (Woolacott & Shumway-Cook, 2022). Data on the impact motion (e.g. sway, pitch and roll, Figure 4) has on postural stability has primarily been derived from the maritime industry.

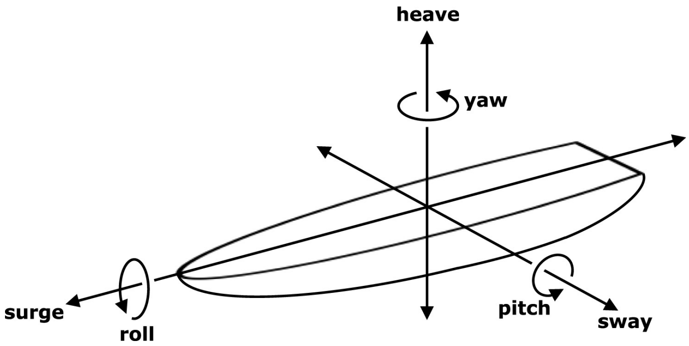

Figure 4: Translation of movement on a vessel

Figure 3 demonstrates that the effect of ship motion on performance can be 'direct', e.g. the performance of tasks requiring balance and co-ordination are directly affected by motion (Powell et al., 1999). Research in both real world (Crossland et al., 2007; Duncan et al., 2010; Duncan et al., 2012; Stoffregen and Smart, 1998) and simulated (Duncan et al., 2016; Matthews et al., 2007) conditions has shown that individuals are required to step more often to maintain balance (also known as a motion-induced interruptions (MII)) and as a result are more unstable. These increases in postural instabilities have been shown to result in a high proportion of fall-related injuries in maritime occupations (43 % of injuries Jensen et al., 2005). Postural challenges in maritime environments are further confounded by the fact that in most instances workers are rarely simply maintaining balance, but rather must perform a job-related task at the same time. To ensure workplace injuries do not occur and job performance does not suffer, both of these tasks must be done efficiently and safely (Duncan et al., 2010). One study aimed to provide a direct comparison of the effects of ship motion on manual materials handling to understand their associated influence on fall risk and performance errors (Duncan et al., 2018). The manual handling task was to lift from the floor up to a table (74 cm) and back (= 1 rep) a 7 kg box once every 10 s for 5 minutes. The task was completed both stationary and during simulated ship motions. The results of this study demonstrated a significant increase in lower limb muscle activation and number of steps needed to maintain balance during the lifting task. These results are important for a number of reasons:

- The increase in lower limb muscle activation results in a greater muscular effort, which is linked to faster rates of fatigue (Kent-Braun, 1999)
- Higher levels of fatigue increase the risk of poor movement patterns and musculoskeletal injury (Kumer 2001) increasing higher risks of overexertion injuries (Holmes et al., 2008)
- The increase in reactive stepping increases the amount of time load is supported on one leg and potentially increases the risk of falling.

This study only assessed a short duration, light load, manual handling task. The magnitude of motion experienced on FOWT during the course of the working day remains to be quantified and the effect longer work durations would have on cumulative fatigue should be assessed. Therefore, to understand the impact of postural stability requirements on job performance and injury risk, it is recommended that studies replicating essential job requirements in simulated environmental conditions of FOWT compared to no motion are undertaken to fully understand the effects of working on floating installations.

2.2.2 Motion illness

A common predisposing factor of motion-induced fatigue is motion illness (sickness), which can elicit physical symptoms that include: sweating, loss of appetite, drowsiness, nausea, headache, stomach awareness (distracting), vomiting, cardiovascular, endocrinological and thermoregulatory changes (Griffin 2012); these symptoms have been reported in individuals exposed to a wide range of motion conditions. The susceptibility to motion sickness exhibits considerable diversity, both among different individuals (inter-subject variability) and within the same person (intra-subject variability) on different occasions and situations (e.g. air vs sea motion-induced illness) (Griffin, 2012). Individuals of various ages, genders, and predispositions may experience motion sickness at some point in their lives; however, specific trends and predisposing factors have been identified:

- Females appear to report more frequent motion sickness than males in a ratio of 1,9 to 1 (Hromatka et al., 2015)
- Sleep deprivation (from all causes) exacerbates motion sickness by disrupting the habituation process of the vestibular system (located in the inner ear and plays a role in maintaining balance and spatial orientation in the body). In maritime settings, this issue is often compounded due to the less-than-ideal sleeping conditions aboard vessels, which hinder the ability to attain restful sleep (Hromatka et al., 2015).
- Research suggests that motion sickness can be a persistent characteristic, whilst certain individuals remain entirely unaffected, others continue to experience symptoms in a variety of motions throughout their lives, without any reduction in susceptibility due to ageing (Guedry, 1991 cited Stevens & Parsons, 2002.)
- An individual's personality and previous encounters with motion play a significant role in shaping their future attitudes and approaches to managing their symptoms when exposed again to motion (Guedry, 1991 cited Stevens & Parsons, 2002).

The stimuli for motion illness is commonly believed to stem from contradictory sensory information originating from internal sources (such as the semicircular canals and the otoliths of the vestibular system) or external sources (such as the eyes and the vestibular system) (Griffin, 2012, Table 2). Habituation (or adaptation) can occur in a few hours and up to several days, in about 5 % of the population it does not occur at all. The time to adapt is generally influenced by individual differences as mentioned above, and by the type of motions encountered (Wertheim 1998).

Table 2: Type of motion cue mismatch produced by various stimuli (adapted from Griffin 2012)

Type of conflict	**Category of motion**	
	Intersensory (Visual [A] – Vestibular [B])	Intrasensory (Canal [A] – Otolith[B])
A and B simultaneously give contradicting or uncorrelated information	– Watching waves* – Use of binoculars in a moving vehicle – Making head movements when vision is distorted by an optical device – 'Pseudo Coriolis' simulation (deflection of moving objects caused by the rotation)	– Making head movement whilst rotating* – Making head movements in an abnormal acceleration environment, which may be constant (hyper- or hop-gravity) or fluctuating (linear oscillation)* – Space sickness – Vestibular disorders*
A signals in the absence of expected B signals	– Cinerama sickness (due to watching movies) – Simulator sickness – Circular vector	– Positional alcohol nystagmus, i.e. involuntary and rhythmic oscillation or movement of the eyes that occurs when a person is exposed to alcohol and assumes certain head positions – Caloric stimulation of semicircular canals (a medical test used to assess the function of the vestibular system) – Vestibular disorders*
B signals in the absence of expected A signals	– Looking inside a moving vehicle without external visual reference (e.g. below deck in a boat)* – Reading in a moving vehicle*	– Low frequency (<0,5 Hz) translational oscillation* – Rotating linear acceleration vectors (changes in speed or direction of motion experienced by an object or individual when undergoing rotational motion*
*Could potentially occur on a FOWT		

Extensive research has been undertaken to identify the factors of motion that induce the most severe nausea and discomfort in sailors. While certain ship movements are known to trigger seasickness in individuals, the precise connection between the ship's motion and the resulting illness remains ambiguous (Stevens & Parsons, 2002). Investigations, encompassing shipboard surveys and controlled laboratory studies, have been carried out to try and explain the impact of various aspects of motion, including type (roll, pitch, and heave in Figure 3), frequency, acceleration, and duration of exposure. Colwell (1989) conducted a comprehensive review of statistical methodologies for predicting the occurrence and intensity of motion sickness.

Additionally, models have attempted to predict the incidence of motion sickness (referred to as MSI, which represents the percentage of individuals who experience vomiting during a two-hour period of ship motion) using various factors, including amplitude, frequency, and duration of exposure to vertical accelerations (O'Hanlon & McCauley, 1974). Furthermore, predictions have been reported based on cumulative exposure ('dose') to vertical accelerations (Lawther & Griffin, 1987), as well as accelerations linked to ship operations in adverse weather conditions (Lloyd & Andrew, 1997). Given that most individuals habituate to motion illness, Colwell in 1994 introduced an 'habituation' function for use with the MSI model (Stevens & Parsons, 2002).

The research suggests a strong link between motion sickness and vertical accelerations at frequencies below 0,6 Hz, with approximately 0,2 Hz demonstrating maximum sensitivity to motion sickness (Griffin, 2012). Table 3 presents the roll/pitch angle and horizontal/vertical acceleration limits in use by the U.S. Navy and U.S. Coast Guard in addition to the MSI and MII. A Motion Sickness Incidence (MSI) rate of 20 % among a ship's crew during a 4 hour exposure is deemed acceptable. This benchmark was established through testing with individuals who have not previously encountered the motion. It is postulated that a crew that has acclimated over several days at sea would likely exhibit reduced levels of motion sickness (Lackner, 2014). In combination it has been shown that a twofold increase in the magnitude of motion, or a fourfold increase in exposure duration, has the effect of doubling the predicted incidence of vomiting. Therefore, the United State Coastguard (USCG) criterion present in Table 3 of 5 % in a 30 minute period represents an equivalent limit.

Table 3: United States Navy and Coastguard operability criteria (Stevens & Parsons, 2002)

Aspect	**Operability criteria**	
	US Navy (NATO STANG 4154)	**US Coast Guard cutter certification plan**
MSI	20 % of crew in 4 hours	5 % in a 30 min exposure
MII	1 tip per minute	2,1 tips per minute
Roll amplitude	4,0° RMS	8,0° SSA
Pitch amplitude	1,5° RMS	3,0° SSA
Vertical acceleration	0,2 g RMS	0,4 g SSA
Lateral acceleration	0,1 g RMS	0,2 g SSA

Note that the data are equivalent, but expressed in different units-root mean square [RMS] and significant single amplitude (SSA = 2 x [RMS]).

Whilst sickness, nausea and the drowsiness and apathy associated with seasickness significantly reduce motivation to conduct required tasks and duties (Stevens & Parsons, 2002), it has also been suggested that the link between symptomatology and performance remains unclear. Much of the research in the area focuses on motion-induced fatigue, which will be discussed in the next section.

2.2.3 Motion-induced fatigue

Peripheral (e.g. the working muscles)

Crew members aboard ships frequently describe feelings of weariness and 'fatigue,' attributing these sensations to the motion of the ship, this sensation does not seem to habituate; instead, it can accumulate and result in a decline in the work performance (Haward et al., 2009). The extent of fatigue encountered offshore is contingent upon various factors, including the vessel's design, motion, vibration, visual and manual challenges, motion sickness, workload, shift patterns, sleep deprivation, lighting, noise, and other elements of the physical environment (Smith et al., 2003). One well documented cause of motion-induced fatigue (MIF) is due to the increased energy expenditure required to maintain balance and posture while working on a moving deck (Stevens & Parsons, 2002). Increases have been observed in oxygen consumption between calm conditions and during roll and pitch motions, with heave motion having little effect. Large variability within and between studies has been found in terms of the increases in metabolic demand observed. Example of these increases include: standing (27 % to 62 % depending on the level of motion, Duncan et al., 2008); treadmill walking (30 %, Heus et al., 1998) and 5 kg lifting task (9 % to 35 % depending on the level of motion, Duncan et al., 2008). Table 4 present the motion characteristics that these increases were observed under.

Table 4: Motion criteria used by Duncan et al. (2008) and Heus et al., (1998) to explore the effect of motion on the metabolic cost of different standing, walking and lifting tasks

	Duncan et al., 2008						**Heus et al., 1998***		
	Low motion			High motion					
Degree of freedom	RMS	Max.	Min.	RMS	Max.	Min.	Amplitude	Parasitical heave	Parasitical translation
Sway (g)	0,11	0,22	−0,22	0,12	0,24	−0,24	NR	NR	NR
Surge (g)	0,23	0,44	−0,44	0,25	0,48	−0,48	NR	NR	NR
Heave (g)	0,24	0,43	0,00	0,26	0,47	0,00	±0,31 m (±0,2 $m.s^{-2}$)	0	0
Pitch (deg/s/s)	3,74	5,30	−5,30	10,24	14,51	−14,50	±5	±0,15 $m.s^{-2}$	0
Roll (deg/s/s)	4,42	6,99	−6,99	11,97	16,97	−16,97	±S[a]	±0,03 $m.s^{-2}$	±0,2 $m.s^{-2}$
Yaw (deg/s/s)	0,00	0,00	0,00	0,00	0,00	0,00	NR	NR	NR
Sway (g)	0,11	0,22	−0,22	0,12	0,24	−0,24	NR	NR	NR

*Motion was always sinusoidal with a frequency of 0,125 Hz.

NR = Not reported

The likelihood of individuals experiencing peripheral motion-induced fatigue on FOWT is unknown and studies would be needed to determine if the motions likely to be experienced on installations are within the range to elicit peripheral fatigue and to what magnitude.

Central
Central fatigue refers to the feeling/perception of fatigue or exhaustion that originates in the central nervous system, particularly the brain; it is different from peripheral fatigue within the muscles. Central fatigue has been linked to lack of motivation, excessive tiredness, and disinclination to work (Haward et al., 2009). Self-reported fatigue has demonstrated high correlations between feelings of fatigue and sleep problems, and between ship motions and sleep problems (Haward et al., 2009). Other factors associated with perceived fatigue were: physical work hazards, working more than 12 hours a day and low job support (Smith et al, 2006). In terms of FOWT consideration therefore needs to be given to:

i. Where workers are going to be located during their shift pattern, i.e. travel from shore either via air or sea each day (extended working hours) or living onboard a support vessel/station (sleep quality).

ii. What shift patterns are to be implemented

iii. The duration of the working day (transfer+ time on the turbine).

2.2.4 Cognitive performance

Cognitive performance relates to tasks that require attention, memory and pattern recognition, included within these are psychomotor abilities, e.g. mathematical reasoning, verbal comprehension, verbal reasoning and visual perception (Stevens and Parsons, 2002). Research in this area is unequivocal, with some early studies reporting that cognitive processing was significantly slower as a result of simulated single frequency heave and roll motions (Wilson, 1986 cited Tipton et al., 2002). Others have shown that motion reduces performance on a psychomotor tapping task but not a computer-based cognitive task (Pingree et al., 1987, cited Tipton et al., 2002). Whilst research both within a ship motion simulator and at sea found no degradation in cognitive performance (Cook & Shipley, 1980; Wertheim, 1998). However, indirect effects on cognitive performance may arise due to motion illness, physical and mental fatigue, particularly after prolonged exposure to challenging weather conditions (Stevens and Parsons, 2002). Therefore, future research in this area of cognitive performance should be careful not to confuse the effects of motion illness with the direct effects of the ship movements on cognitive activity, and focus on cognitive tasks required on a FOWT.

2.2.5 Summary

This section of the review touched on the plethora of literature that examines the impact of motion on human performance. The key points are summarised below:

i. *Compromised movement patterns* – A large portion of an individual's work involves manual handling. If individuals are having to make more MIIs, optimal movement patterns could be compromised and injury risks increased.

ii. *Increased energy expenditure and muscle activation* – Completion of essential job tasks will require a greater physical demand (increases in oxygen demand range between 9 % to 63 %). Consequently, individuals may fatigue quicker or fitness level may need to be increased in order to have a greater reserve capacity to accommodate the additional physical demands.

iii. *Motion Illness* – A strong link between motion sickness and vertical accelerations has been shown at frequencies below 0,6 Hz, with approximately 0,2 Hz demonstrating maximum sensitivity to motion sickness. Whilst sickness, nausea and the drowsiness and apathy associated with seasickness significantly reduce motivation to conduct required tasks and duties, it has also been suggested that the link between symptomatology and performance remains unclear.

iv. *Motion-induced fatigue (peripheral)* – Individuals do not seem to habituate to peripheral fatigue, instead it can accumulate and result in a decline in the work performance. The extent of fatigue encountered is a combination of various factors, including the vessel's design, motion, vibration, visual and manual challenges, motion sickness, workload, shift patterns, sleep deprivation, lighting, noise, and other elements of the physical environment.

v. *Motion-induced fatigue (central)* – Central fatigue has been linked to a lack of motivation, excessive tiredness, and disinclination to work. Self-reported fatigue has demonstrated high correlations with sleep problems, which can be linked to motion. Other factors associated with perceived fatigue are: physical work hazards, working more than 12 hours a day and low job support.

vi. *Cognitive performance* – The effects of motion on cognitive performance are unclear. However, indirect effects on cognitive performance may arise due to motion illness and physical and mental fatigue, particularly after prolonged exposure to motion.

3 RECOMMENDATIONS

3.1 MITIGATION STRATEGIES

A number of mitigation strategies have been suggested within the literature (Bittner & Guignard, 1985; Stevens & Parsons, 2002) these have been adapted for FOWT and only include human factors (Table 5), and not factors that involve design and systems engineering (e.g. operation and maintenance of machinery and equipment) and operating solutions (e.g. strategic and tactical planning to minimise risk).

Table 5: Mitigating the adverse effects of motion (adapted from Bittner & Guignard, 1985)

Approaches	Methods
Human factors engineering	1. Arrangement and design of individual working spaces 2. Location and orientation of individual support stations (e.g. SOVs) 3. Work and task design 4. Display/control design and placement – to reduce head turning (Khalid et al., 2011) 5. Optimisation of turbine environmental factors (e.g. provide an external visual frame of reference, Rolnick & Bies, 1989) 6. The use of anti-vibration devices
Enhancing natural human resistance to motion effects	1. Optimisation of work/rest and duty/leave cycles 2. Habituation and oscillatory motion training 3. Specific task training in motion environment 4. Appropriate selection of individuals (Medical and Physical Employment Standards) 5. Provision of adequate sleep 6. Adequate training to identify and manage fatigue 7. Optimisation of team sizes
Modifying adverse physiological reactions to motion	1. Optimisation of individual fitness and mental well-being 2. Optimisation and treatment of the immediate physiologic state 3. Medication*
*The use of medications requires a medical evaluation to determine whether this approach would be of benefit and not put individuals at additional risk	

3.2 FUTURE RESEARCH

It is recommended that a body of work be undertaken to provide a comprehensive body of research that will anticipate and evaluate potential motion scenarios for FOWT. This includes assessing the potential effects on inducing motion illness and fatigue, aiming to comprehend the implications for worker performance, health, and safety. This can lead to the formulation of tailored best practice recommendations for FOWT and the creation of advisory packages for organisations, regulators and policymakers. A proposed outline is presented in Table 6.

Table 6: Proposed programme of work (*Likely need to occur once a FOWT is in operation)

Phase	**Proposed work**	**Who could undertake this**	**Recommended time scales**
1) Identification of motion	Collate and identify the motion parameters expected working in all areas of FOWT, with considerations made to scalability of turbines and the likely growth in size– desk top study	G+ and its members	6 to 12 months
2) Implications of motion	Determine whether the identified motions are likely to impact individuals, e.g. motion illness, motion-induced fatigue, cognitive function – desk top study	G+ in collaboration with a university	3 months
At this stage if motions are not detected that would impact individuals no further action needed			
3) Design/ Modelling	Can turbine and floater designs be modified to minimise the motions that will impact individuals, with considerations made to scalability of turbines and the likely growth in size – computer modelling/design studies	Turbine designers in collaboration with specialist in the area of motion and humans	12 to 24 months
At this stage if motions can be designed out that would impact individuals no further action needed			

Table 6: Proposed programme of work (*Likely need to occur once a FOWT is in operation) (continued)

Phase	Proposed work	Who could undertake this	Recommended time scales
4) Assessing the impact of motion	a) Review the current recommendation on the regular use of medication to mitigate motion illness – recommended review by the Energy Institute's Health and Technical Committee b) Identify all the essential tasks across all job roles that could be affected by motion – Field study c) Quantify the magnitude and cumulation of motion illness likely to be experienced working under the proposed motion characteristics of FOWT and investigate the impact on the performance of essential job tasks – Field observations and laboratory study d) Identify and quantify the differences in movement patterns, energy expenditure and muscle activation when undertaking essential job tasks that occur when working under the proposed motion characteristics of FOWT – Laboratory study e) Determine if there is an effect of motion on job specific cognitive task when working under the proposed motion characteristics of FOWT – Laboratory study f) Consider the differences mode of transport (e.g. air or sea) to the turbine has on motion illness responses and workability		24 to 36 months per study

Table 6: Proposed programme of work (*Likely need to occur once a FOWT is in operation) (continued)

Phase	Proposed work	Who could undertake this	Recommended time scales
5) Enhancing human resistance to motion effects	a) Determine the optimal work/rest and duty/leave cycles* – desk-based and field study b) Determine the optimal habituation and oscillatory motion duration and training – laboratory study c) Develop and design specific task training in a motion environment – laboratory study d) Determine whether current medical standards and physical capacity assessments are fit for purpose and validate any recommended changes – desk based and laboratory study e) Develop training to identify and manage fatigue – desk based and laboratory study f) Understanding the team sizes required to manage the physical demands and complete the essential work tasks in the allotted time* – desk based and field study		
6) Modifying adverse physiological reactions to motion	a) Determine if current fitness and mental well-being support is adequate for individuals, if not develop and implement job specific fitness and well-being programmes – desk-based study and potential laboratory study b) Determine if any interventions/tools are available that could reduce the effects of motion illness or motion-induced fatigue – desk based and laboratory study c) Investigate the use of medication in reducing the effects of motion illness or motion-induced fatigue		
7) Transferring science into practice and policy	Translating phases 4 to 6 science into policy and practice	G+ in collaboration with a university	
8) Following up	Evaluate the effectiveness of interventions adopted from phases 5 and 6	G+ in collaboration with a university	

4 GLOSSARY OF TERMS

FOWT -	floating offshore wind turbines (a turbine only attached to the seabed via mooring . . . lines and anchors, floating on the surface of the water).
MIF –	motion-induced fatigue (feelings of weariness and 'fatigue,' attributed to the motion of the ship)
MII –	motion-induced interruptions (situations where the vessel's movements cause . . . . . . disbalance to an individual, where they must cease their task to stabilise themselves).
MSI -	Motion Sickness Incidence (the percentage of individuals who experience vomiting . . during a two hour period of ship motion)
N –	not reported
O&M –	operations and maintenance (daily requirements to maintain facilities and ensure . . . . normal operations)
RMS -	root mean square (the square root of the mean of the squares of specified values).
SOV –	service operation vessel
SSA –	significant single amplitude ("the variance estimate of the measured ship motions . . . including surge, sway, heave, roll, pitch, yaw, and lateral and vertical accelerations at various locations on the vessel." (https://www.ittc.info/media/7999/75-02-01-08.pdf)).
USCG –	United States Coastguard

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